THERMAL AND FLUID ANALYSIS OF THE BIGELOW EXPANDABLE ACTIVITY MODULE (BEAM)

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BEAM Mission Background

- Bigelow Aerospace developed BEAM in partnership with NASA as a 2 year technology demonstration mission
  - Expandable habitats weigh less and take less transport volume than traditional metallic modules
  - Expandable habitats show great promise to support human activity in space for both stand-alone commercial stations and moon/mars bases

- BEAM launched in April 2016 on SpaceX CRS 8 (within Dragon trunk) and was expanded on station in May 2016
  - The module has been out-performing expectations on-orbit since its expansion and will continue to serve a variety of important missions on ISS
- ATA Engineering responsible for supporting BEAM thermal design and verifying all thermal/IMV requirements over various mission phases

- Only ISS ICD requirements driving the BEAM design while berthing and operational on ISS considered herein

BIGELOW EXPANDABLE ACTIVITY MODULE (BEAM)

ISS ICD THERMAL REQUIREMENTS

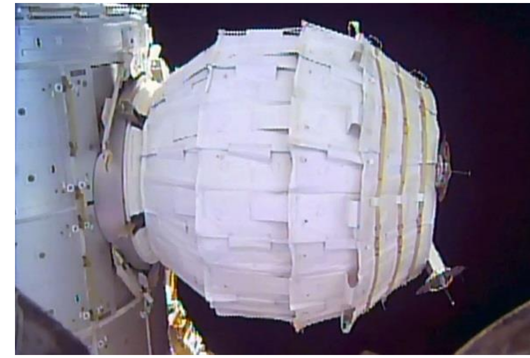
On-Orbit BEAM Thermal Requirements

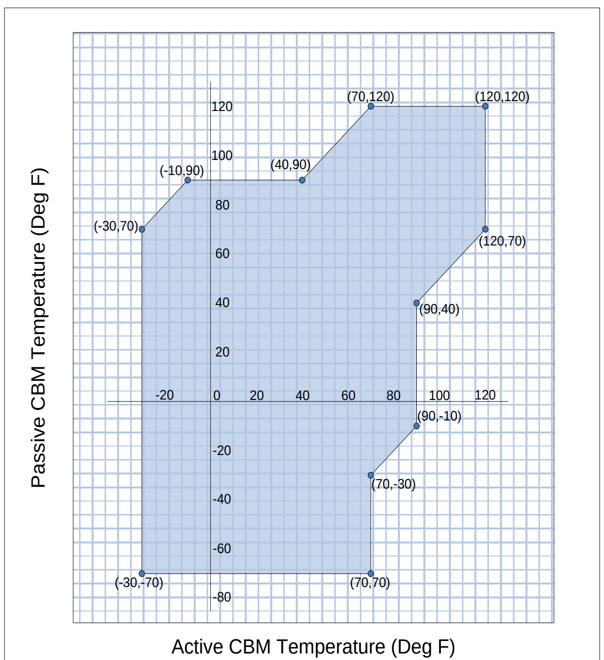
Subject	Requirement
Circulate Atmosphere Intramodule	2/3 air volume airflow velocity between 10 and 40 ft/min
Circulate Atmosphere Intramodule	Volume of air within airlock area with average velocity less than 7 ft/min shall not exceed 5% total BEAM volume
Passive Interface Temperature	During berthing operations, PCBM and ACBM shall be within allowable CBM temperature range
Passive Interface Temperature	During pressurization and prior to IMV, PCBM/vestibule shall reach above 60 °F within 72 hours to preclude the presence of any condensation.
Passive Interface Temperature	After pressurization and IMV initiation, PCBM surface temperatures shall be between 60 °F and 113 °F. This must be met under abiabitic B.C., i.e. independence from heat transfer across ACBM/PCBM interface or radiation heat transfer within Node 3
Thermal Environments	While attached to the ISS, the BEAM shall meet all functional and performance requirements during nominal operations in the ISS flight attitude envelope
Preclude Condensation	While attached to the ISS, the BEAM shall prevent condensation on BEAM interior surfaces, except on vestibule surfaces during the time of pressurization of the vestibule volume. Total allowable time for condensation and subsequent drying after vestibule pressurization will be limited to 72 hours.
Internal Touch Hot Temperature Hazard	Internal touch temperature shall be less than 113 °F during operations
Internal Touch Cold Temperature Hazard	Internal touch temperature shall be greater than 32 °F during operations
External Touch Temperature Hazards for Incidental Contact	For incidental contact, temperatures shall be between -180 and +235 °F
External Touch Temperature Hazards for Unlimited Contact	For unlimited contact, temperatures shall be between -45 and +145 °F

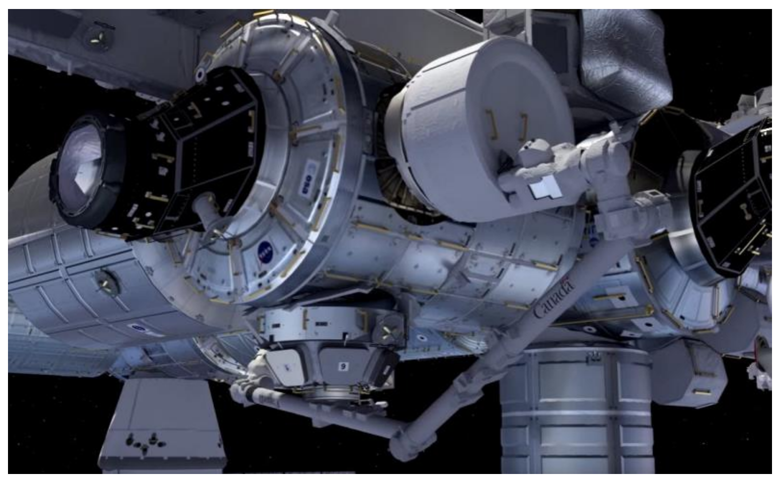
Ref: SSP 57239, "Bigelow Expandable Activity Module (BEAM) to International Space Station (ISS) Interface Control Document International Space Station Program", Feb, 2012 (Ref 1)

BEAM Temperature Allowables

	Berthed and Pressurized on Node 3		
Components	**Min. (˚F)**	**Max. (˚F)**	**Source (min; max)**
MMOD MLI	-220	220	Material limits
MMOD	-220	220	Material limits
Bladder	53	113	Condensation limit; internal touch limit
Electronics	32	113	Internal touch limits
Batteries	32	113	Internal touch limits
Inflation/AV Valves	32	113	Internal touch limits
TA/Bulkheads	53	113	Condensation limit; internal touch limit
PCBM	53	113	Condensation limit; internal touch limit
Handrails	-45	145	External unlimited touch limits
FRGF	-250	266	Material limits





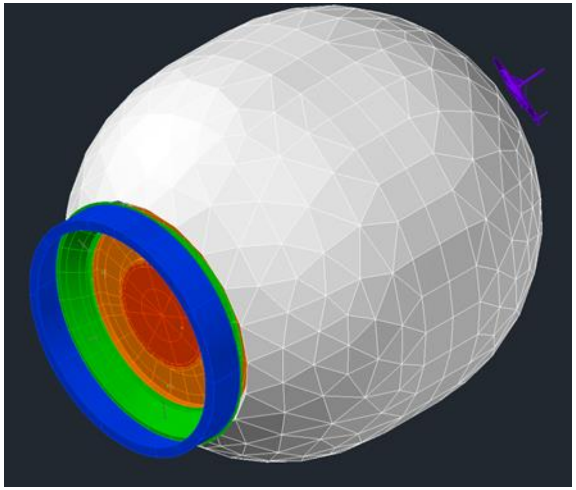


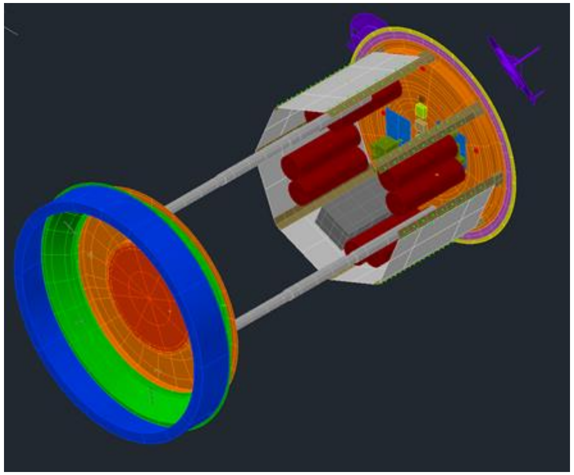
BIGELOW EXPANDABLE ACTIVITY MODULE (BEAM)

THERMAL MODEL DESCRIPTION

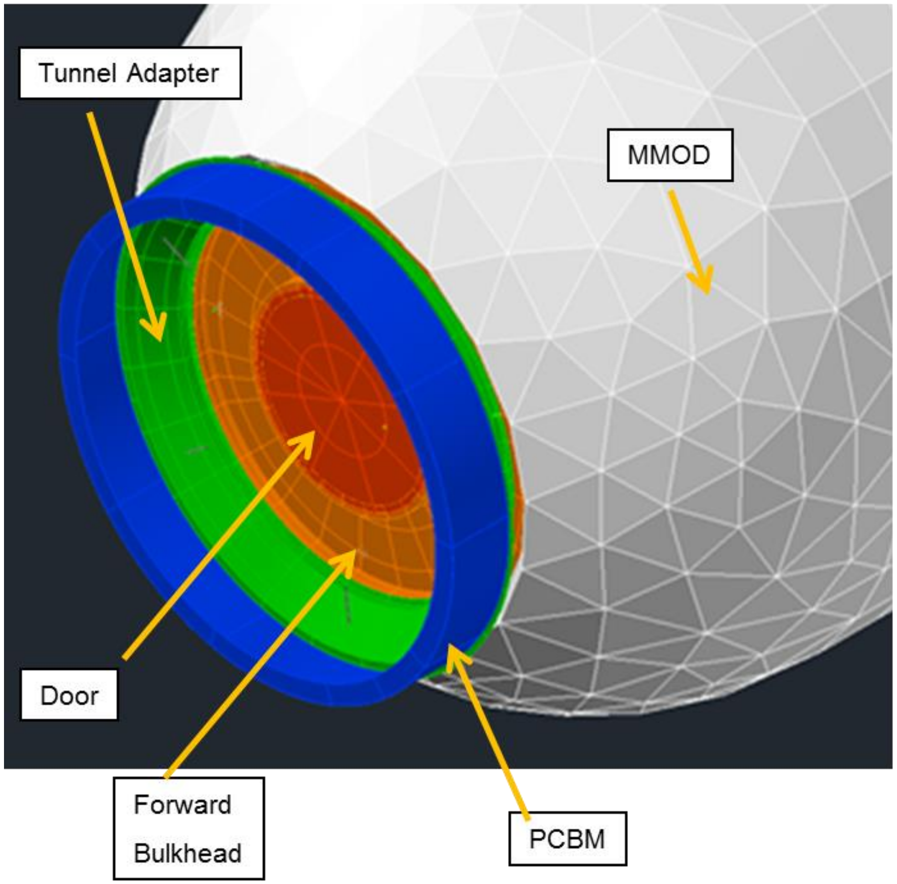
BEAM Thermal Model

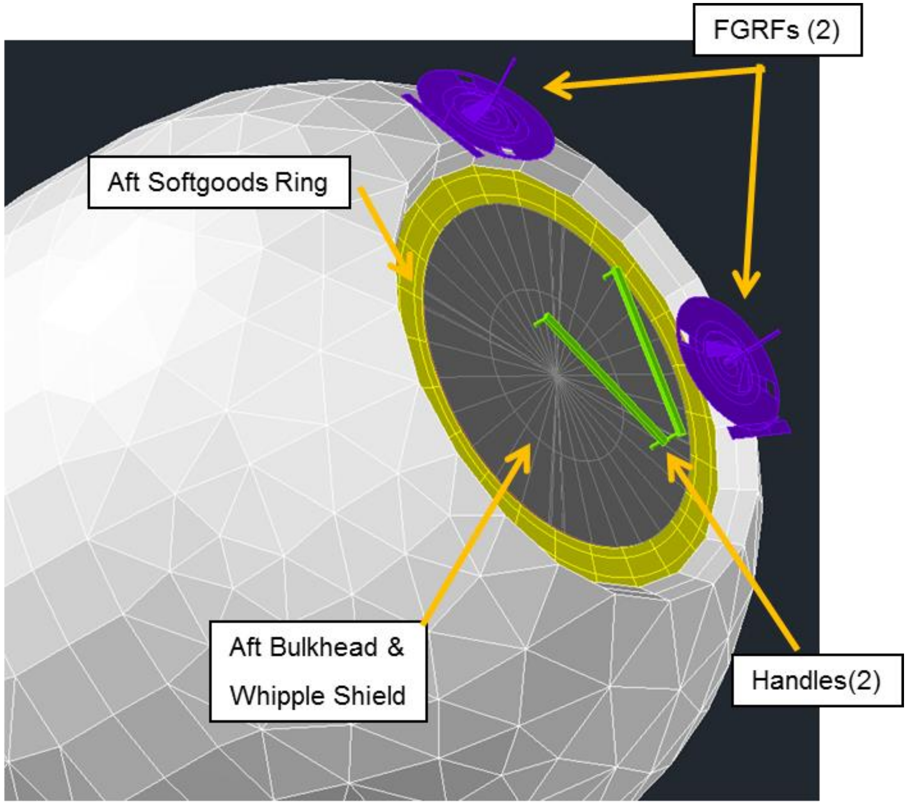
- Detailed Thermal Desktop model developed to predict transient on-orbit temperature profile for all components
  - Model contains over 9200 nodes, 2.5M radiation couplings
  - Models mechanical interfaces and individual components
  - During development, model results checked against hand calculations to ensure continuity, feasibility of results
  - Integrated with ISS and detailed Node 3 Thermal Models
  - Includes test-correlated effective emittance through MMOD





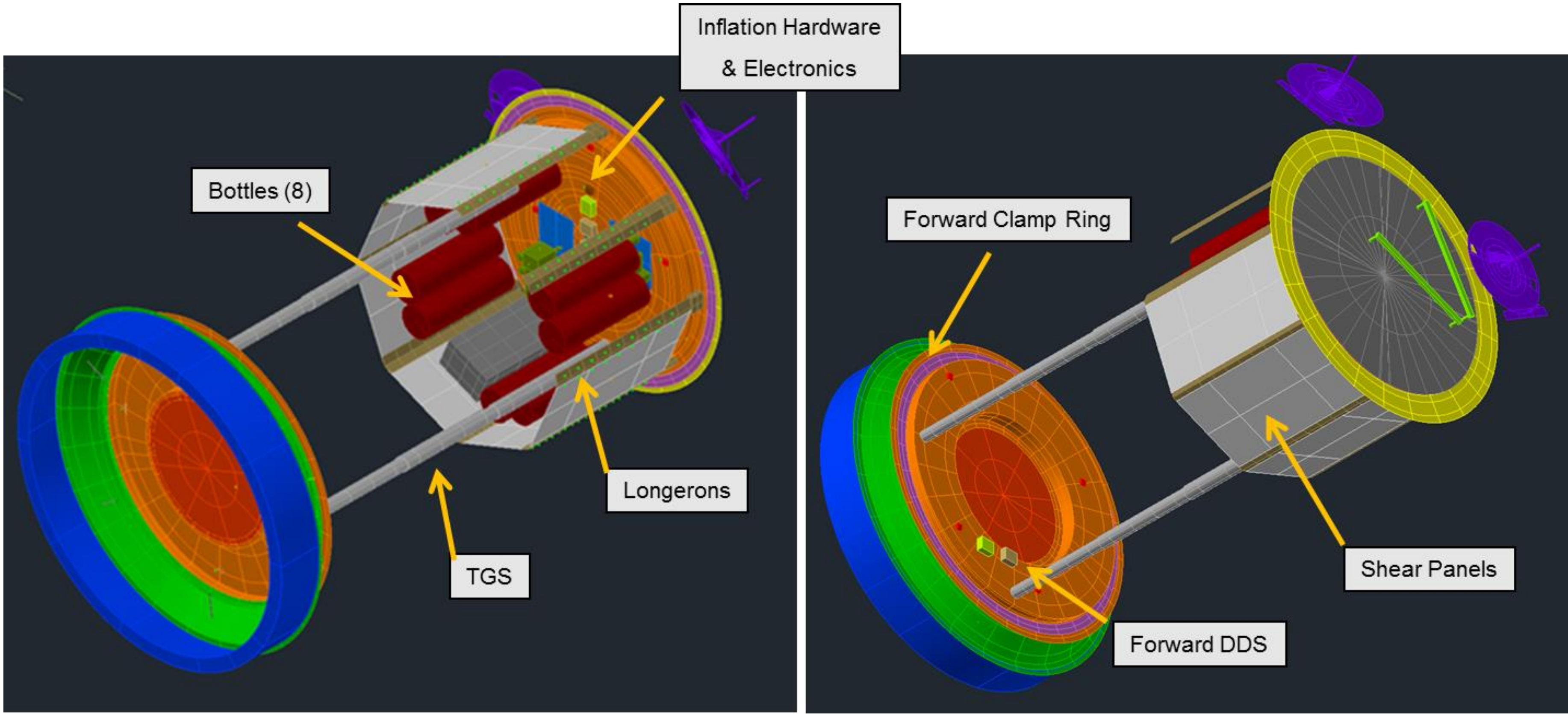
BEAM Model Exterior Components





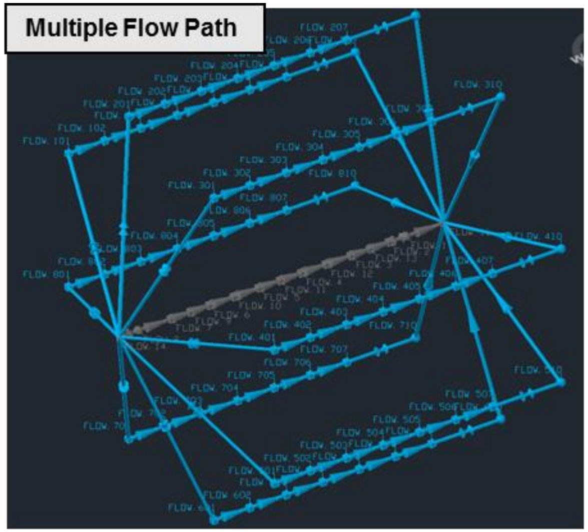
MLI Not Shown

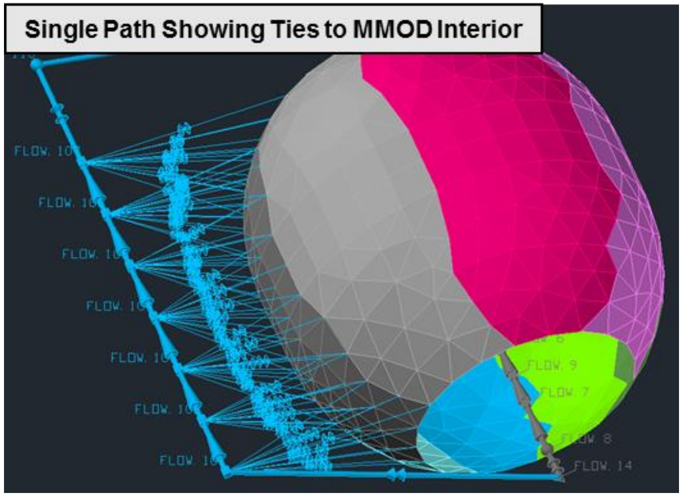
BEAM Model Interior Components



Internal Air Flow Modeled as 1D Network

- BEAM thermal system model includes multi-path flow model of IMV airflow
  - Includes center and eight peripheral flow paths
  - Flow paths defined correspond to CFD heat transfer coefficients
  - Includes heat transfer with interior surfaces as well as MMOD
  - IMV flow inlet conditions taken from SSP 57239 for hot and cold scenarios
  - Allows for evaluation of transient non-uniform environmental heating





BEAM Model Material Properties

Thermal Material	K, BTU/hr/ft/°F	Cp, BTU/lb/°F	ρ, lbm/ft^3	Source
Aluminum 6061-T6	97.0	0.23	173	Gilmore, Thermal Control Handbook[2]
MMOD In-Plane	0.17	0.23	104	Fabric Thermal Conductivity paper[3]
MMOD Thru Thickness	0.047			Fabric Thermal Conductivity paper[3]
Stainless Steel	9.4	0.12	504	Gilmore, Thermal Control Handbook[2]

Optical Surface	α	ε	α/ε	Source
Anodized Aluminum	0.48	0.82	0.58	Gilmore, Thermal Control Handbook[2]
Beta Cloth	0.37	0.88	0.42	Gilmore, Thermal Control Handbook[2]
Stainless Steel	0.47	0.14	3.4	Gilmore, Thermal Control Handbook[2]
White Paint (BOL)	0.19	0.92	0.21	Gilmore, Thermal Control Handbook[2]
White Paint (EOL)	0.40	0.92	0.43	Gilmore, Thermal Control Handbook[2]

Effective Emittance	ε*	Source
MMOD from bladder to MLI	Proprietary	Bigelow test data
MLI	0.05	Engineering estimate for multilayer insulation

Emissivity Testing performed for MMOD

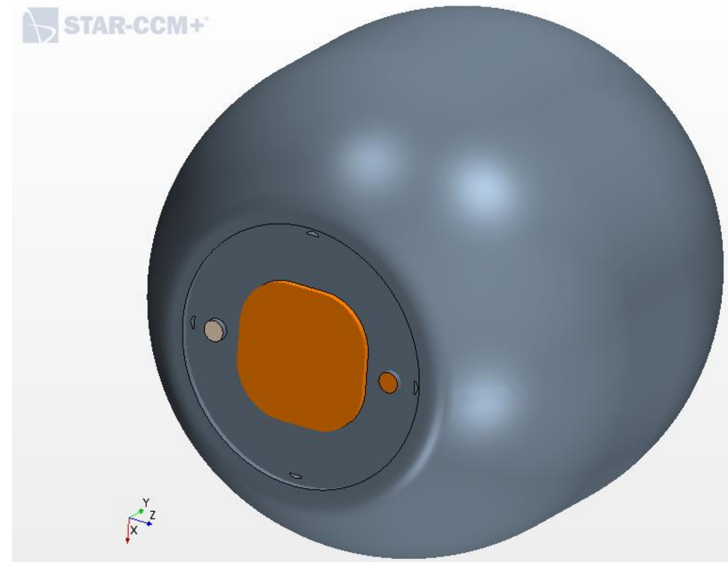
- ATA supported Bigelow with effective emissivity testing for MMOD construction
  - Critical component of BEAM thermal design
- ATA developed thermal model of test configuration and correlated it to test results
  - Thermal model test configuration used to predict effective emissivity of MMOD flight configuration
  - Value incorporated into system thermal model
  - Process reviewed and approved by Bigelow and NASA

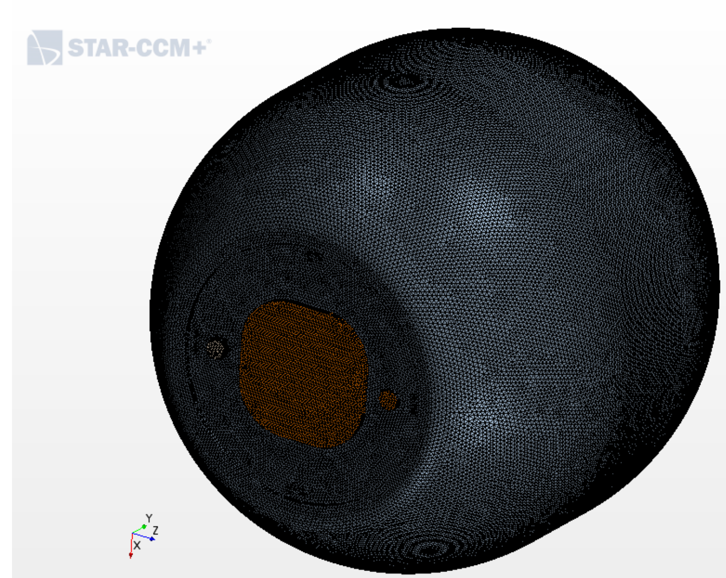
BIGELOW EXPANDABLE ACTIVITY MODULE (BEAM)

CFD MODEL DESCRIPTION & RESULTS

BEAM CFD Modeling Overview

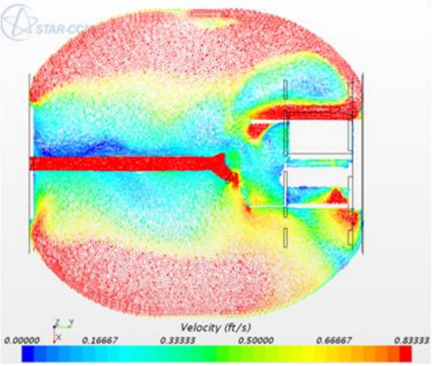
- CFD model of inflated BEAM configuration developed
  - Consists of nearly 4.4 million cells
  - k-ε turbulent model
  - steady-state
  - Represents closed & open hatch configurations
  - Predicts velocity profiles and heat transfer coefficients
  - Assumes IMV flow characteristics as described in SSP 57239 Section 3.2.3
    - Inlet flow rate at 120 CFM (closed hatch) and 135 CFM (open hatch)
    - Inlet flow temperature between 65 F and 81 F, dewpoint between 40 F and 60 F
- Internal surface temperature from thermal model

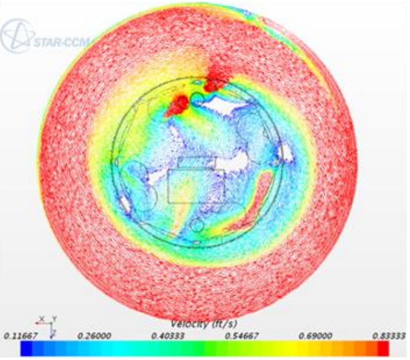




BEAM CFD Results

- Airflow predictions compared favorably with NASA CFD analysis
- Pressure drop through BEAM module is 0.14 in-H20
- CFD analysis predicts volume of stagnant air is below the 5% threshold
- CFD models predict higher velocity flow percentage (51%) above 40 ft/min than allowable in ICD (<33%)





OPEN HATCH (135 CFM)	BEAM (CAD 03/27/2014)
Total Volume (ft^3)	556.3
Percentage of air velocity < 10 ft/min (>6 inch from walls)	4.3%
Percentage of air velocity > 40 ft/min (>6 inch from walls)	49.2%
Percentage of air velocity > 45 ft/min (>6 inch from walls)	44.3%
Percentage of air velocity > 50 ft/min (>6 inch from walls)	38.5%
Percentage of air velocity > 55 ft/min (>6 inch from walls)	31.1%
Percentage of air velocity > 60 ft/min (>6 inch from walls)	22.8%
Percentage of air velocity > 70 ft/min (>6 inch from walls)	5.0%
Percentage of air: 10 ft/min < Velocity < 40 ft/min (>6 inch from walls)	46.5%
Percentage of air velocity < 7 ft/min (total volume)	1.4%
Maximum air velocity ft/min (>6 inch from walls)	1065.4

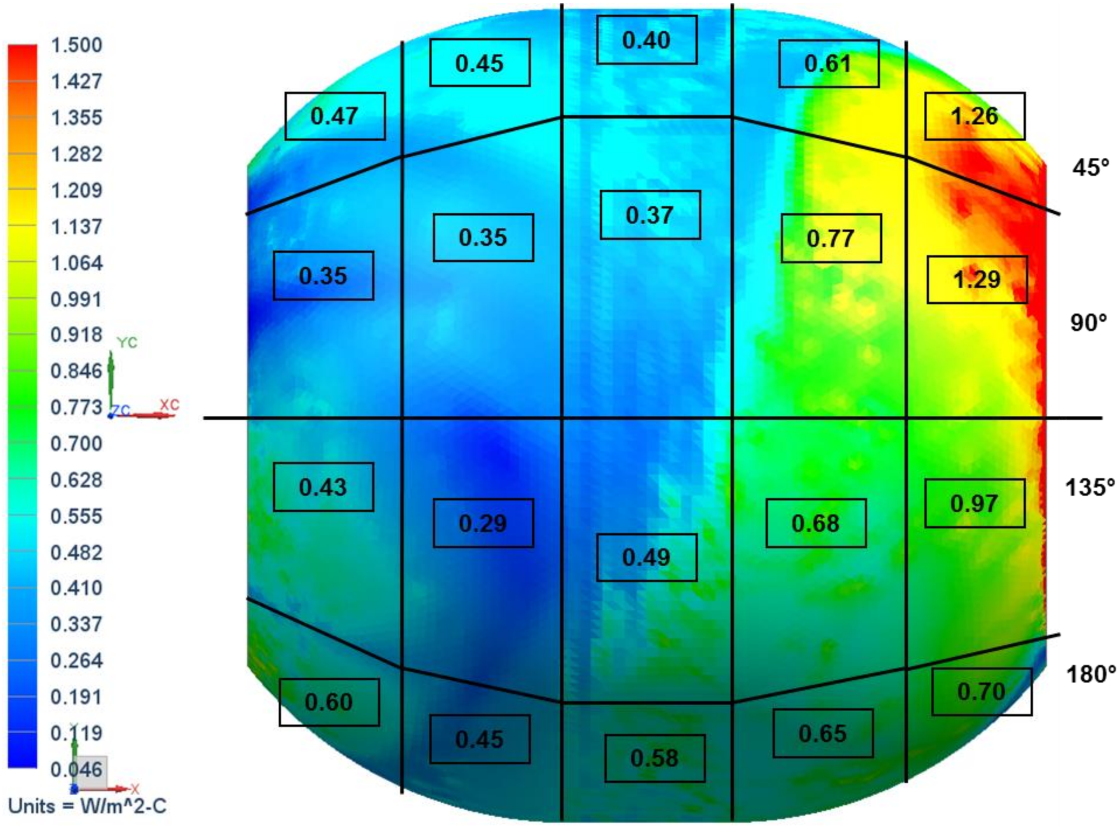
Airflow Compliance Summary:

- All requirements satisfied excluding higher velocity limits
- An exception was accepted for the higher velocities

CLOSED HATCH (120 CFM)	BEAM (CAD 03/27/2014)
Total Volume (ft^3)	556.3
Percentage of air velocity < 10 ft/min (>6 inch from walls)	8.5%
Percentage of air velocity > 40 ft/min (>6 inch from walls)	47.4%
Percentage of air: 10 ft/min < Velocity < 40 ft/min (>6 inch from walls)	44.1%
Percentage of air velocity < 7 ft/min (total volume)	2.9%

Heat transfer coefficients calculated

Heat Transfer coefficients averaged for 20 sections on the BEAM interior



Circumferential degree (YZ-plane)	Section number in X direction	Averaged h (W/m^2)
45	1	0.40
45	2	0.45
45	3	0.47
45	4	0.61
45	5	1.26
90	1	0.37
90	2	0.35
90	3	0.35
90	4	0.77
90	5	1.29
135	1	0.49
135	2	0.29
135	3	0.43
135	4	0.68
135	5	0.97
180	1	0.58
180	2	0.46
180	3	0.60
180	4	0.65
180	5	0.70

BIGELOW EXPANDABLE ACTIVITY MODULE (BEAM)

THERMAL ANALYSIS METHODOLOGY & RESULTS

Critical Analysis Cases Identified

ATA, Bigelow and NASA identified design driver cases to be evaluated as part of BEAM thermal design

Critical Cases included:

- Packed in Dragon, Freeflight, hot and cold
- Packed in Dragon, at ISS node 2, hot and cold
- **Packed, berthing/berthed at ISS node 3, hot and cold**
- **Inflated, berthed at ISS, hot and cold**
- Inflated, berthed at ISS, no IMV, hot and cold
- Inflated, berthed at ISS, hot, w plume impingement
- Various ISS orientations, YPR and beta angle combinations (75˚ to -75˚) results in 220+ cases

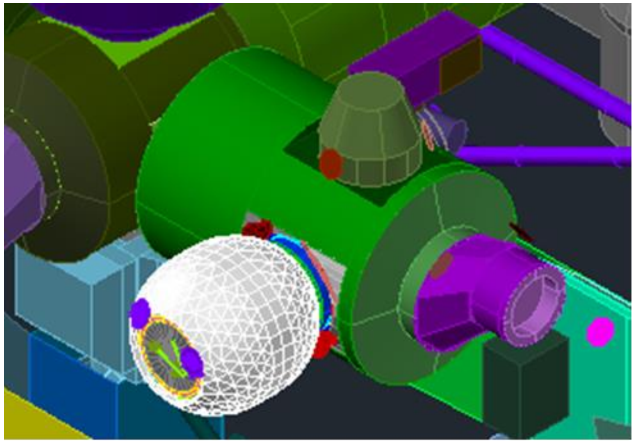
Common modeling assumptions

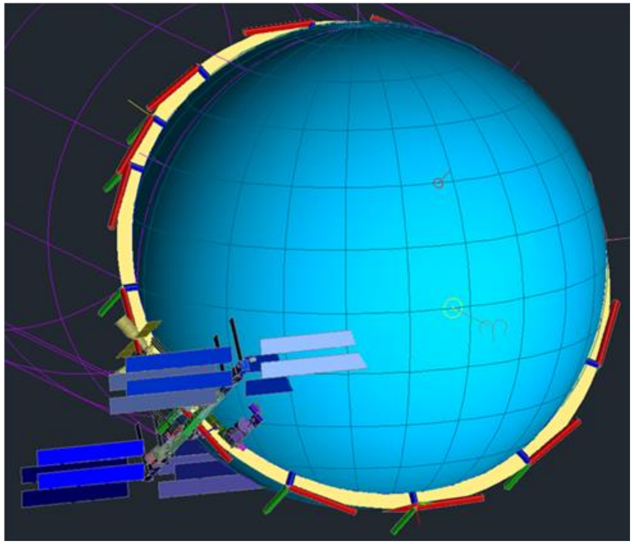
- ISS in +XVV or +YVV (both +Z nadir) orientation
  - Nominal YPR (000) = 0,−2.5, 0
  - Extreme (HLL) = 15,-20,-15
- Hot = 450 BTU/hr ft^2 solar, 81 BTU/hr ft^2 earth IR, 0.4 albedo, EOL surface properties
- Cold = 419 BTU/hr ft^2 solar, 65 BTU/hr ft^2 earth IR, 0.2 albedo, BOL surface properties

BEAM Analysis Description

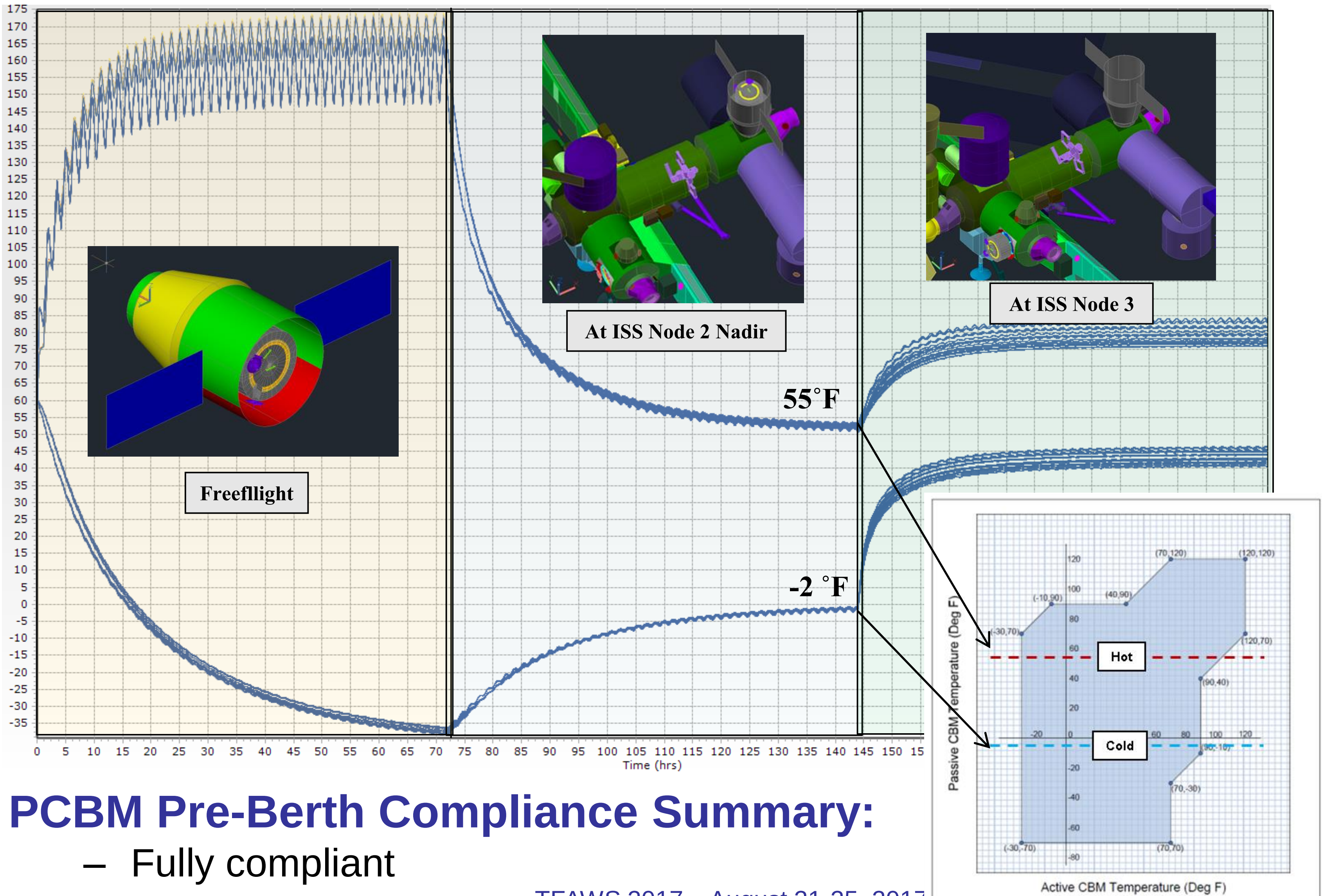
Analysis Methodology

- Developed lower resolution "screening" model to evaluate full case matrix
  - Screen model results only used for comparative purposes, not for ICD validation
- Detailed model results presented for driving cases
  - Screen model results match well with detailed model
- Run 70+ orbits to reach orbital "steady-state" condition, i.e. only thermal variation coming from environment.
- IMV flow
  - Inlet flow rate at 120 CFM (closed hatch) and 135 CFM (open hatch)
  - Inlet flow temperature between 65 F and 81 F, dewpoint between 40 F and 60 F





Node 3 Pre-Berth ACBM/PCBM Temps

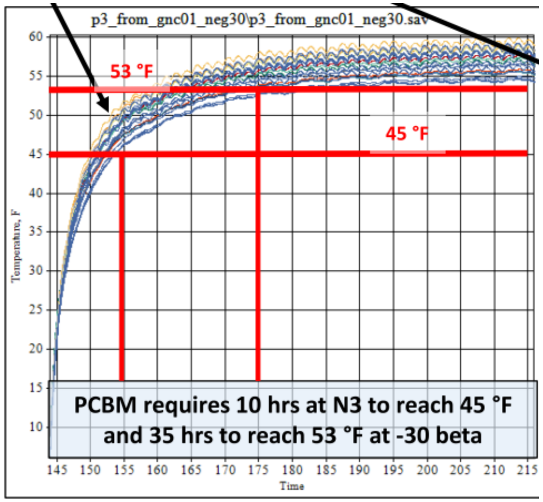


PCBM Pre-Berth Compliance Summary:

– Fully compliant

Node 3 Pressurized PCBM Temps (no IMV)

PCBM Temperature Profile for -30 Beta

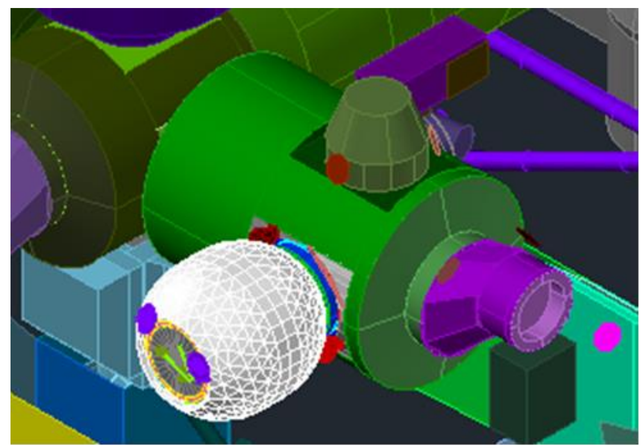


Vestibule Steady-State Temperature vs. Beta Angle

COMPONENT	MIN TEMP (+45 BETA)	MIN TEMP (+30 BETA)	MIN TEMP (0 BETA)	MIN TEMP (-30 BETA)	MIN TEMP (-60 BETA)
BM AVVA	32.8 °F	32.8 °F	22.2 °F	13.6 °F	2.2 °F
BM HATCH	59.5 °F	59.0 °F	**51.5 °F**	**47.8 °F**	**42.2 °F**
BM FWD BULK	55.6 °F	55.9 °F	**48.5 °F**	**44.0 °F**	**37.9 °F**
BM TUN ADPT	58.3 °F	58.2 °F	**51.0 °F**	**46.7 °F**	**40.9 °F**
BM PCBM	63.1 °F	62.8 °F	56.7 °F	54.0 °F	**49.7 °F**
N3 ACBM	68.6 °F	68.5 °F	65.2 °F	64.5 °F	63.1 °F
N3 CPAS	70.0 °F	69.9 °F	66.5 °F	65.9 °F	64.9 °F
N3 HATCH	69.1 °F	68.8 °F	64.9 °F	64.1 °F	62.7 °F

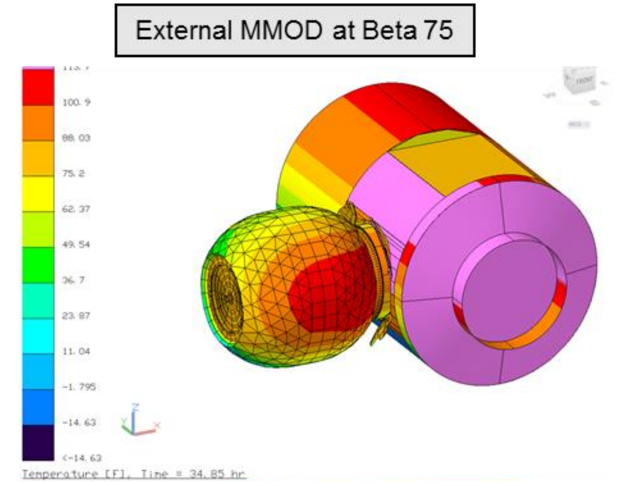
PCBM Compliance Summary:

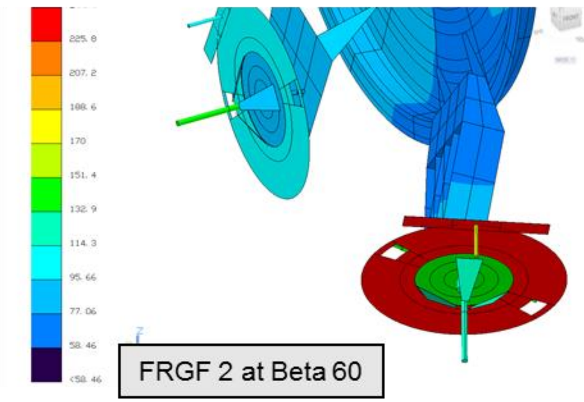
- The PCBM reaches an orbital steady state temperature of at least 53 ˚F only at beta −30 and above for cases when there is no IMV flow
- NASA permitted lower dew point of 53 ˚F and operational constraint on beta angles during berthing sequence



Hot Cases with 81F IMV

81 IMV Hot Case	000 Predicted T (°F)	Beta 75, HLL Predicted T (°F)	Max Allowable T (°F)
MMOD MLI	189	201	220
MMOD	120	150	220
Bladder	82	88	113
Electronics	88	90	113
Batteries	82	92	113
Inflation/AV Valves	80	85	113
TA/Bulkheads	84	**114**	113
PCBM	91	105	113
Handrails	134	121	145
FRGF	249	242	266



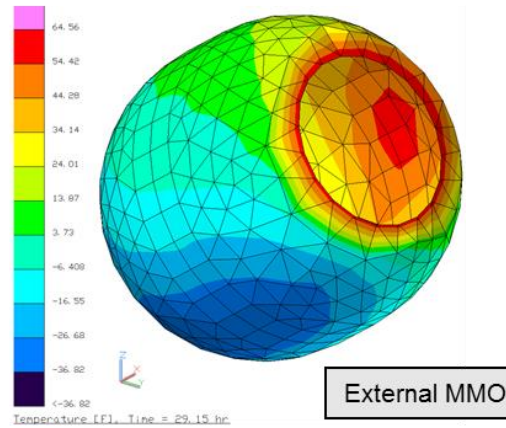


ICD Compliance Summary:

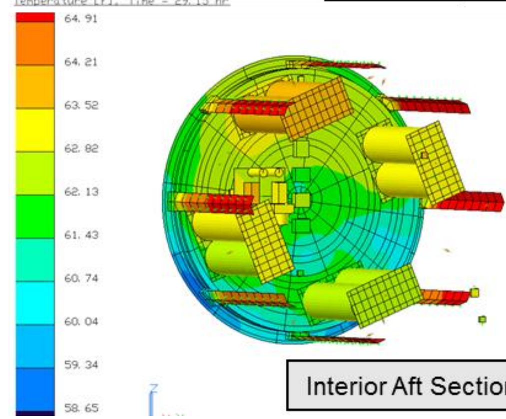
- Results for both nominal and extreme YPR orbits show no exceedences of component operational allowables
- An exception was accepted for tunnel adapter temperature 1˚F above touch temperature limit

Cold Cases with 72F IMV

72 IMV Cold Case	000 Predicted T (°F)	Beta -75, HLL Predicted T (°F)	Min Allowable T (°F)
MMOD MLI	-179	-200	-220
MMOD	-38	-55	-220
Bladder	61	57	53
Electronics	61	59	32
Batteries	62	57	32
Inflation/AV Valves	61	60	32
TA/Bulkheads	56	56	53
PCBM	61	57	53
Handrails	9	6	-45
FRGF	-60	-65	-250



External MMOD at Beta -75



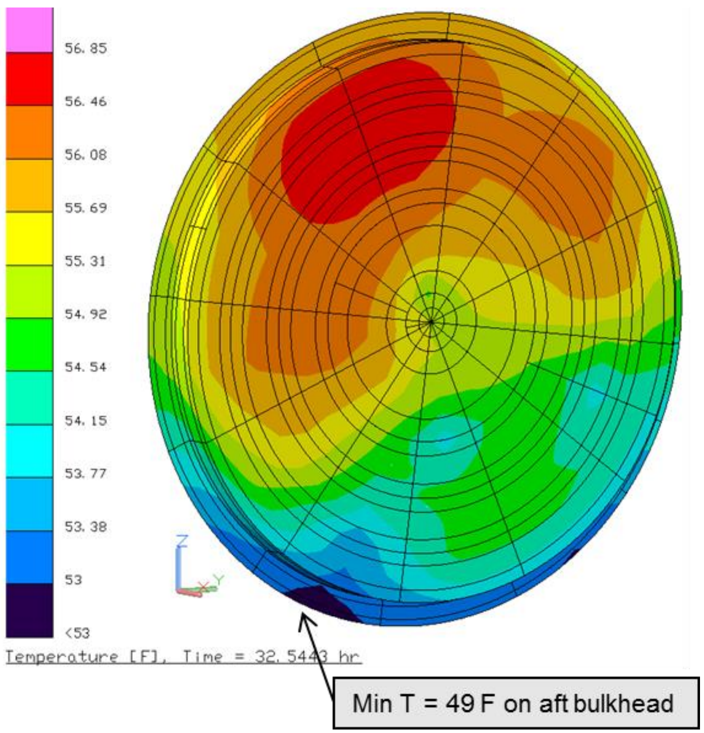
Interior Aft Section at Beta = -75

ICD Compliance Summary:

– Fully compliant with all thermal requirements and allowables with reduced dew point of 53 ˚F

Cold Cases with 65F IMV

65 IMV Cold Case	000 Predicted T (°F)	Beta -75, HLL Predicted T (°F)	Min Allowable T (°F)
MMOD MLI	-179	-200	-220
MMOD	-41	-61	-220
Bladder	54	48	53
Electronics	55	53	32
Batteries	55	51	32
Inflation/AV Valve	55	56/53	32
TA/Bulkheads	53	49	53
PCBM	57	53	53
Handrails	5	3	-45
FRGF	-60	-68	-250



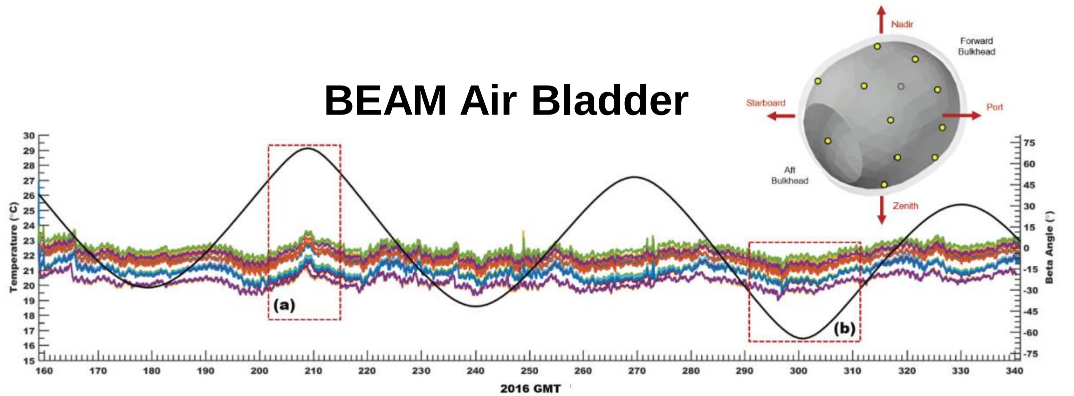
ICD Compliance Summary:

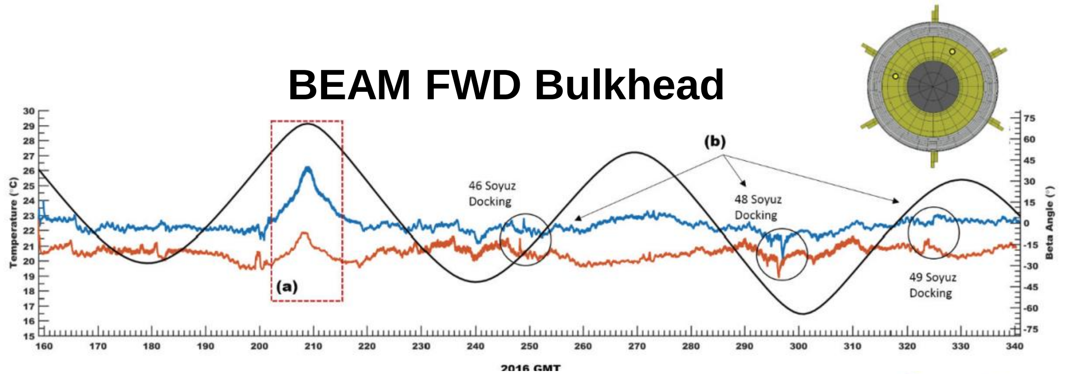
- Fully compliant with all thermal requirements and allowables with reduced dew point of 53 ˚F under all nominal YPR orbital conditions
- The "ICD extreme" cold case with 65 ˚F IMV in conjunction with a high yaw ISS orientation is considered a very unlikely occurrence
- An exception was accepted for bulkhead temperature below condensation limit for this extreme HLL case

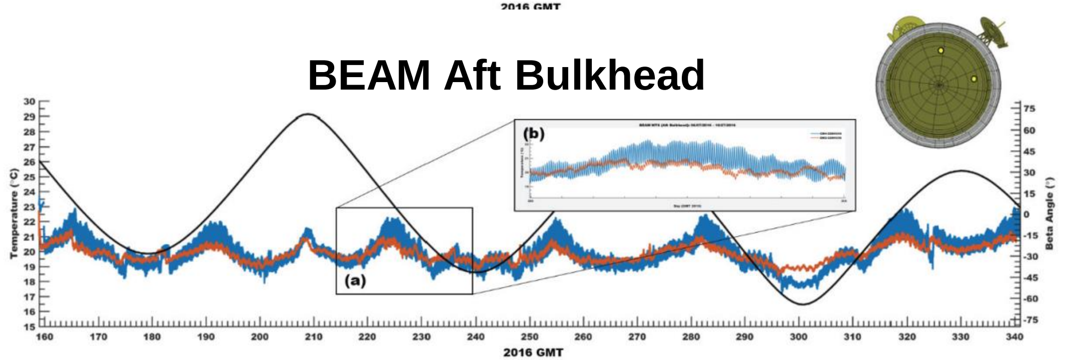
Actual vs. Predicted Temperatures Compare Favorably

- BEAM temperatures have been monitored by NASA (Ref 4)
- Simulation temperatures bound on-orbit temperatures
- Potential reasons for differences include:
  - Worst-case conditions simulated more extreme conditions than actual BEAM environment
  - Under-prediction of IMV heat transfer (Ref 4)

	Simulation Temperatures		BEAM 2016 Temperatures	
Component	Min (°F)	Max (°F)	Min (°F)	Max (°F)
Bladder	61	82	66	75
Forward Bulkhead	60	93	66	80
Aft Bulkhead	56	84	63	73







Conclusions

- Detailed thermal and CFD models of BEAM were created and analyzed
  - Thermal model included 1D flow network based on CFD results and utilized test correlated ε* value of softgoods
  - 220+ critical orbital cases with varying ISS orientations, YPR and beta combinations were analyzed using screening model
  - Nominal and extreme cases analyzed with detailed model to verify compliance with ICD requirements
- BEAM meets thermal requirements with few exceptions
  - Passive design (no heaters, only ISS IMV)
- Predicted design temperatures bound actual on-orbit temperatures
- Favorable performance of BEAM to date leading to likely extension of BEAM mission beyond initial 2 years
  - Shows promise for future inflatable space exploration habitats

BIGELOW EXPANDABLE ACTIVITY MODULE (BEAM)

BACK-UP SLIDES

Glossary

ACBM – Active Common Berthing Mechanism

BEAM – Bigelow Expandable Activity Module

CBM – Common Berthing Mechanism

FRGF – Flight Releasable Grapple Fixture

IMV – Intermodule Ventilation Assembly

ISS – International Space Station

MLI – Multilayer Insulation

MMOD - Micrometeoroids and Orbital Debris

PCBM – Passive Common Berthing Mechanism

PDGF – Power and Data Grapple Fixture

SPDM – Special Purpose Dexterous Manipulator

SSRMS – Space Station Remote Manipulator System

References

1. NASA document SSP 57239, “Bigelow Expandable Activity Module (BEAM) to International Space Station (ISS) Interface Control Document International Space Station Program”, Feb, 2012
2. Gilmore, D. G., editor, “Spacecraft Thermal Control Handbook, Volume 1, 2nd Edition,” AIAA, 2002
3. Yoshihiro, Yamashita et al “Effective Thermal Conductivity of Plain Weave Fabric and it s Composite Material Made from High Strength Fibers” in Journal of Textile Engineering (2008) vol 54, no 4, pgs 111-119
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BEAM CFD Modeling Flow Requirements

3.2.3 ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS) INTERFACES

3.2.3.1 RECEIVE INTERMODULE ATMOSPHERE

The BEAM will receive intermodule atmosphere from Node 3.

3.2.3.1.1 INTERMODULE ATMOSPHERE RECEIVE CHARACTERISTICS

3.2.3.1.1.1 INTERMODULE ATMOSPHERE RECEIVE TEMPERATURE

The BEAM will receive intermodule air from Node 3 at a temperature range of 65 to 81 °F (18.3 to 27.2 °C).

3.2.3.1.1.2 INTERMODULE ATMOSPHERE SUPPLY AND RECEIVE PRESSURE

The maximum pressure loss in the Intermodule Ventilation (IMV) valve ducting (supply from Node 3 to BEAM and return from BEAM to Node 3) on the BEAM side of the Node 3 to BEAM interface (including the IMV jumpers) shall not exceed 0.44 inches of water (109.6 Pa) at a minimum flow rate of 135 Cubic Feet per Minute (CFM) (3.8 m^3/min).

3.2.3.1.1.3 INTERMODULE ATMOSPHERE RECEIVE RATE

A. The BEAM shall receive a minimum flow rate of 135 CFM (3.8 m^3/min) of intermodule air from Node 3 during normal operation with both the Node 3 BEAM Hatches Open.

B. The BEAM shall receive a minimum flow rate of 120 CFM of intermodule air from Node 3 during nominal closed hatch flow operations.

3.2.3.2.1.1 INTERMODULE ATMOSPHERE RETURN TEMPERATURE

The BEAM shall return intermodule air to Node 3 at a temperature range of 65 to 86 °F (18.3 to 30.0 °C). The temperature of the air supplied by the BEAM to Node 3 shall be, at a minimum, 5 °F greater than the dew point.

3.2.3.2.1.3 INTERMODULE ATMOSPHERE RETURN RATE

A. The BEAM shall return a minimum flow rate of 135 CFM (3.8 m^3/min) of intermodule air to Node 3 for normal operation with both the Node 3 and BEAM Hatches Open.

B. The BEAM shall return a minimum flow rate of 120 CFM of intermodule air to Node 3 during nominal closed hatch flow operations.

3.2.3.2.1.4 INTERMODULE ATMOSPHERE RETURN HUMIDITY

The BEAM shall return intermodule atmosphere with a dew point between 40 to 60 °F (4.5 to 15.6 °C).

3.2.3.2.1.5 INTERMODULE ATMOSPHERE HEAT LOAD

The BEAM shall return a maximum sensible heat load of +220W exchanged through the intermodule atmosphere interface.

3.2.3.7 BEAM INTERNAL PROPERTIES

3.2.3.7.1 CIRCULATE ATMOSPHERE INTRAMODULE

The air velocity through 2/3 of the internal cabin habitable volume greater than the layer 6 inches (150mm) from the cabin aisleway surfaces shall be between 10ft/min (0.051m/s) and 40ft/min (0.203m/s). To avoid pockets of stagnant air, air velocities outside the layer 6in (150mm) from the cabin aisleway surfaces averaging less than 7ft/min (0.036m/s) shall not sum to equal a volume larger than 5% of the total internal cabin volume.

These requirements set boundary conditions for CFD analysis, as well as requirements for return airflow that CFD will help establish compliance